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13. ABSTRACT (Maximum 200 words) As stated in the abstract of this DURIP proposal, quoted below, the goal is to deploy a state of the art sodium lidar transmitter and detector, based on recent innovations in sodium technology, at ALOMAR (Arctic Lidar Observatory for Middle Atmosphere Research) to take the advantage of the existing twin, steerable ALOMAR telescope mirrors (1.8 meter in diameter each) for thermal and dynamic studies in an arctic mesopause region. This objective has been largely completed and the lidar performance has been successfully tested. this lidar system is now being used for research.					
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## FINAL REPORT

Research Title: A Sodium Lidar Transmitter for Wind and Temperature Measurements at Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR)

Principal Investigator: Chiao-Yao She

Office Phone: (970) 491-6261 FAX: (970) 491-7947

Mailing Address: Physics Department

Colorado State University

Fort Collins, CO 80523-2875

E-Mail Address: joeshe@lamar.colostate.edu

AFOSR Program Manager: Maj. Paul Bellaire

Research Project: F49620-99-1-0151 P00001

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## Objectives of the Research Instrumentation

As stated in the abstract of this DURIP proposal, quoted below, the goal is to deploy a state-of-the-art sodium lidar transmitter and detector, based on recent innovations in sodium technology, at ALOMAR (Arctic Lidar Observatory for Middle Atmosphere Research) to take the advantage of the existing twin, steerable ALOMAR telescope mirrors (1.8 meter in diameter each) for thermal and dynamic studies in an arctic mesopause region. This objective has been largely completed and the lidar performance has been successfully tested. This lidar system is now being used for research of co-PI (Fritts) and PI (She) sponsored by AFOSR.

"We propose the development of a state-of-the-art sodium resonance lidar and its installation at the ALOMAR lidar/radar observatory in northern Norway for comprehensive studies of middle atmosphere dynamics. The lidar would be developed using a new technique for achieving a very narrow line width, high frequency stability at the sodium D<sub>2</sub> resonance line, and sufficient output power to allow for high-precision dual-beam measurements of winds and temperatures at altitudes from ~80 to 105 km. The transmitter system would be mated with the large twin collector optics currently used by twin high-power Rayleigh-Mie-Raman lidars capable of similar measurements between ~10 and 80 km. In addition to the sodium lidar transmitter requested, our European colleagues will bear the costs for a data acquisition system and for an intricate modification to the focal boxes to allow simultaneous operation of two lidar systems. These lidars will be used jointly with other ALOMAR instrumentation and *in-situ* measurements from the adjacent Andoya Rocket Range for the most comprehensive studies of middle atmosphere dynamics possible anywhere on the globe. As such, it would provide the most complete definition possible of the dynamical influences in the important polar region at altitudes where dynamics, solar inputs, and chemistry all contribute to the structure and variability of the middle atmosphere. With the proposed sodium lidar, ALOMAR observations would provide key sensitivity to mesopause dynamics, microphysics, structure, and variability at the lower boundary of the ionosphere and the Space Weather environment which are now central to Air Force interests. This development would also yield an observational instrument suite that would be on line for solar maximum, would define the responses to variable solar and lower atmosphere forcing throughout this period, and would thus contribute measurement capabilities and understanding of atmospheric and ionospheric processes of considerable importance to the national defense."

## Relevance of the Instrumentation

Global change and space weather and their possible adverse impacts to human activities have become issues not only for scientific study but also of public concern. In view of this urgency and the fact that the Arctic middle and upper atmosphere may provide an early signature for climatic change, the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) was established at Andoya, Norway (69°N, 16°E) in 1994 to perform regular observations with an arsenal of radio and optical equipment as

well as rocket and balloon launch facilities near-by. From the beginning, ALOMAR was designed to house three lidars, a Rayleigh-Mie-Raman (RMR) lidar, an Ozone lidar and a Sodium lidar. Both the RMR and the Ozone lidar have been in regular operation since 1995, and the recent birth of a state-of-the-art Sodium lidar has provided the missing link, making ALOMAR an unique observatory for atmospheric dynamics and ozone studies between 10 and 110 km in the auroral zone.

This new instrument is named the "ALOMAR Weber Sodium Lidar", in honor of the late Dr. Edward Weber, an ionospheric physicist at the Air Force Research Laboratory, and the late Louis R. Weber, former Head of the Colorado State University Physics Department from 1939 to 1964.

### **Innovative Technology deployed**

The Weber lidar represents innovative sodium resonance technology. In addition to commercial lasers and optics purchased, much engineering design and construction based on past Colorado State technology developments funded by NSF/CEDAR program were introduced and constructed at Colorado State prior to deployment, which makes this an unique instrument anywhere in the world at present. Specifically, these include:

- 1). a new Continuous Wave (CW) laser at the sodium resonance wavelength of 589 nm, achieved via sum-frequency generation for stable narrowband operations;
- 2). Doppler-free sodium resonance spectroscopy for precision frequency control;
- 3). tandem acousto-optic modulators for three-frequency wind and temperature measurements; and
- 4). Faraday filters for narrowband "skynoise" (light contamination) rejection, enabling full daylight operations.

In addition, to simultaneously accepting both Sodium and the existing RMR lidar signals, the German Institute of Atmospheric Physics (IAP) underwrote the expensive modification of the focal boxes to re-configure the twin telescopes, which is a first attempt anywhere, thus an innovation in its own right.

### **Deployment and First Observation**

After a trip to ALOMAR near the end of May to investigate the observatory and to arrange shipment details, the PI went back to Fort Collins on June 8 to help and speed up the implementation of the instrument. On June 23<sup>rd</sup>, four crates of lidar transmitter parts were shipped by air to Andoya, Norway. Our technical team was scheduled to be in ALOMAR on July 19, starting lidar installation. It was planned as shown in the following chart that Joe Vance, the key student on the project, and the PI would spend about one month in ALOMAR and the two postdocs each would be there for about 3 weeks with 4 days overlap between August 1<sup>st</sup> and 4<sup>th</sup>. During these 4 days when all 4 members of the team were present, data acquisition was to take place, weather permitting. Things did not happen as planned. There was considerable unexpected technical problems. To start with, one of the receiving fibers was damaged during the shipment, limiting lidar operation to one beam and one of the telescope useless. Considerable electrical and electronic noise

problems were also encountered, along with problem in the coating of the sum-frequency crystal. Suffice to say, after countless 14-hour days of laboratory work and trouble shooting, these difficulties were overcome and the system was finally ready on August 10<sup>th</sup>. By this time, the unusually gorgeous weather continuing for more than two weeks turned to heavy clouds and raining. Partially cloudy condition with patches of blue sky finally appeared on Aug. 13<sup>th</sup>. The first Na signal was then detected. Fair weather finally prevailed on Aug. 14<sup>th</sup> giving us a chance to complete a continuous 24-hour plus observation until early morning of Aug. 16<sup>th</sup>, 10 hours before the PI was scheduled to leave for Oslo.

Joe Vance	[7/19 ←————→ 8/17]
Zhilin Hu	[7/19 ←————→ 8/4]
Joe She	[7/21 ←————→ 8/16]
Biff Williams	[8/1 ←————→ 8/17]

The first Na lidar operation, using one vertical beam and one telescope was quite successful and the quality of the received signal fully demonstrated the expected performance. The first atmospheric Na signal was detected on 09:50:15 UT, Sunday, August 13, 2000 under daylight, partly cloudy conditions. The first 24 hours observation with 3-frequency operation, providing information of temperature and line-of-sight wind was completed ~1:30 UT, Wednesday, August 16, 2000. Fair weather prevailed at ALOMAR Monday night, and all three lidars operated between 21:00, Aug. 14 and 01:00, Aug. 15 with quality data, demonstrating the potential of clustered lidar observation at ALOMAR. The second beam was installed in early October and off-zenith operation will be initiated in Spring-Summer, 2001.

A second brief campaign by Williams and the P.I. took place in the beginning of October to further test the instrument and its data acquisition capability under both day and night conditions. In this trip, a new receiving fiber was installed, completing two-beam operation as originally planned. In addition, 12 hours observation was made, limited by weather conditions. The Co-PI, Dave Fritts and Dr. Hoppe of Norwegian Defence Research Institute as well as Per Torbo of Norwegian Space Center were at ALOMAR, witnessing the operation of this unique new instrument.

### **Personnel and Contribution**

The Principle Investigator, Chiao-Yao (Joe) She was awarded a Fulbright Researcher grant to spend 5 months in Norway between May and October, 2000. This facilitated our installation effort considerably. Much credit for the successful implementation goes to the lidar group in the Physics Department at Colorado State University (CSU). A large team contributed to the development of this unique instrument, including faculty member, Dave Krueger, postdocs, Biff Williams and Zhilin Hu, former graduate students, Hans Moosmüller (now at the University of Nevada) and Vince Vasoli (now at Raytheon),

current graduate students, Joe Vance, Titus Yuan and Jim Sherman, as well as undergraduate students, Phil Acott and Kam Arnold.

Over 70% of the new Sodium lidar was funded by U.S. Air Force Office of Scientific Research (AFOSR) with Defense University Research Instrumentation Program (DURIP). The balance of the funding was secured by the ALOMAR founders, Ulf von Zahn (IAP), Eivind Thrane (Norwegian Defence Research Institute) and Kolbjørn Adolfsen (Andoya Rocket Range), as well as Franz-Jesef Lübken (IAP) and Dave Fritts of Colorado Research Associates (Co-Ra). This U.S. funding represents a major and continued participation of U.S. scientists in ALOMAR, where instruments from German, Norwegian, French, British and Canadian scientists are already in place. The positive benefit of strong international collaboration in climatic research is being fully demonstrated at ALOMAR.

### **Tests and Initial results**

As mentioned, after finding Na signal, a continuous 26 hours of observation in August under daylight condition were completed. Later in October, a 12-hour observation was made consisting of 5 daytime hours and 7 nighttime hours. These results (shown in Fig. 1) have now been analyzed, testifying the successful implementation of the instrument. Included for comparison are the August and October mean temperature profiles in Lübken and von Zahn (JGR, 1991).

### **Measurement Accuracy, Future Improvement and Continued Operation**

When mated with the large twin, steerable ALOMAR mirrors, the ALOMAR Weber Na lidar will achieve its unique measurement capabilities with an averaged transmitter power of only 0.6 W per beam, yielding a power-aperture product of  $1.5 \text{ Wm}^2$  with each telescope. At night at the altitude of peak sodium density (around 92 km), this will enable measurement precision of 0.5 Kelvin for temperature, and 1.5 meters per second for wind velocity averaged over a  $\pm 1$  km depth for 5 minutes (or other averaging combinations yielding equal photon counts). The lidar provides reduced precision at higher and lower altitudes with another factor of  $\sim 2$  reduction during daytime.

Due to a necessary synchronization between the c.w. light and the pulsed light in the lidar system, the wind measurement accuracy is typically less than that stated above. However, its temperature measurement, which is less demanding, is fairly good. There is no conceptual problem in the needed synchronization, and the device is under design and its completion is expected this coming summer. Then, the expected precision for both temperature and wind measurements will be achieved. Considerable gravity wave activity has been observed in the initial Na density and temperature profiles obtained by the test runs of Weber lidar. Future simultaneous temperature and wind measurements would provide more complete information on the gravity wave activities at ALOMAR.

The Na lidar initially will be used for research based on temperature and wind measurements by P.I. Joe She of CSU and co-PI, Dave Fritts of Co-Ra and their

colleagues, under continuing funding from Space Science of AFOSR managed by Paul Bellaire to maximize the benefits to the Air Force of the DURIP investment. Correlative observation with other ALOMAR instrumentation, both passive and active, are anticipated. The Weber lidar will gradually be automated and used by scientists in the ALOMAR community to pursue their collaborative research goals.

### **Publication and Publicity**

Although no scientific paper based on this DURIP project has been written, a poster paper has been presented at the Fall AGU meeting. An invited oral presentation was given at the OSA topical meeting, "Optical Remote Sensing of the Atmosphere" in February, 2001. The title and reference for these presentation flows:

J. D. Vance, C. Y. She, B. P. Williams, Zhilin Hu, and David A. Krueger, "ALOMAR Weber Sodium Lidar: A new lidar for measuring temperature and dynamics in the Arctic mesopause region" SPA-Aeronomy Poster, December 15-19, 2000, AGU fall meeting.

Chiao-Yao She, "ALOMAR Weber Sodium Lidar: A new lidar for measuring temperature, winds, and dynamics in the Arctic mesopause region", Invited Paper OWD1 - OSA/Optical Remote Sensing of Atmosphere (Feb. 5-8, 2001).

The ALOMAR story of the Weber Sodium Lidar has been written up in 3 different publications and one newspaper. These include an article, "Laser instrument probes the lower boundary of the ionosphere" in the AFOSR Sep-Oct 2000 publication of Research High Lights, and an article, "A new lidar is born at ALOMAR" in the CEDAR Post, Vol. 41, January 2001.

While the PI was working with Biff Williams in ALOMAR in October 2000, Dr. Ulf Hoppe of Norwegian Defence Institute, the Co-PI, Dr. Fritts visited. A science writer of Norwegian Space Center, Per Torbo, visited us and interviewed Fritts, Hoppe and She on the role and importance of lidar research at ALOMAR. The installation of our Sodium lidar has finally completed the lidar equipment anticipated since ALOMAR was founded in 1994. Our lidar installation triggered this interview and led to an article about ALOMAR in the October 12<sup>th</sup> issue of Aftenposten (Oslo's major paper) and an special ALOMAR issue of Norwegian Space Center publication, "Aurora", October, 2000.



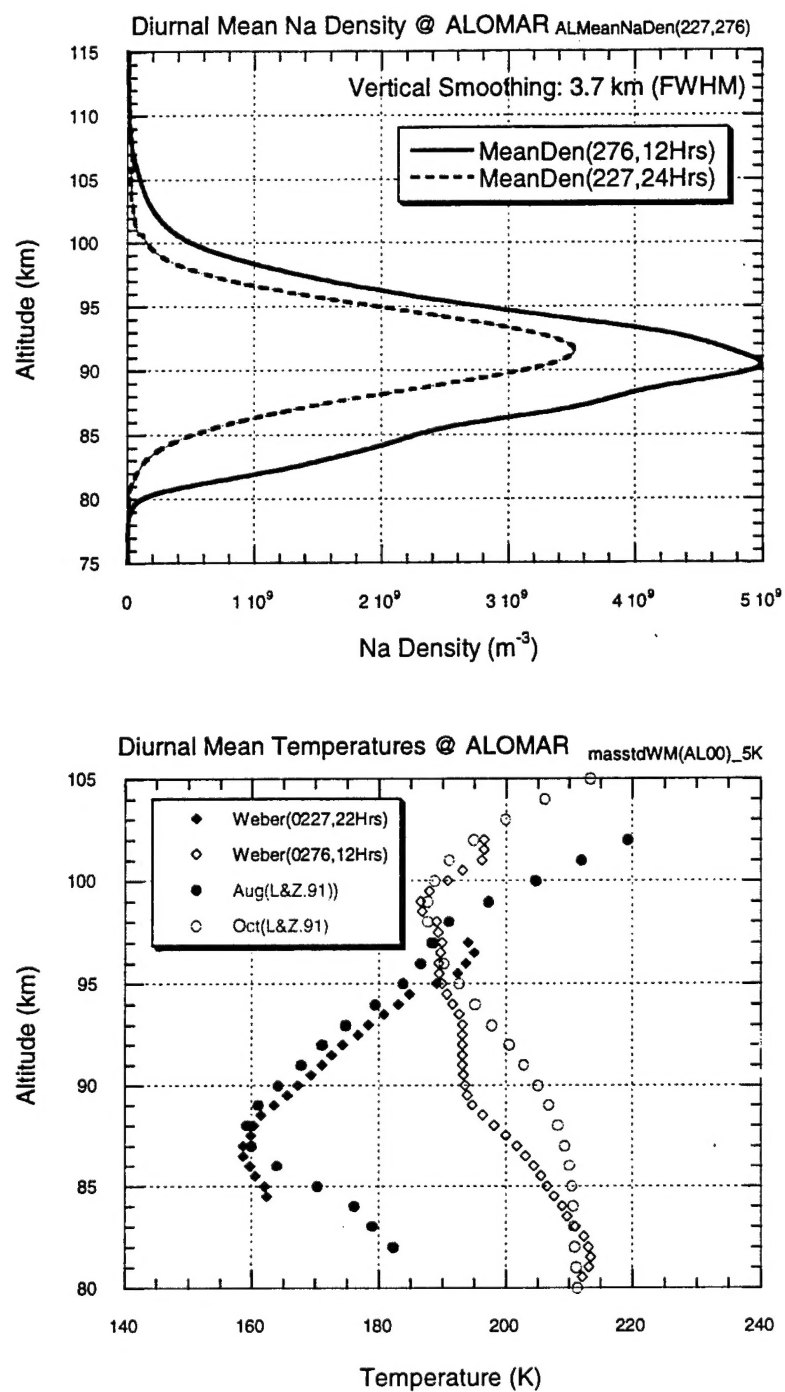


Fig. 1 Weber Lidar Observation: Initial Diurnal Mean Na Density and Temperature Profiles (Day 227 and 276, 2000) at ALOMAR (69N, 16E), compared with earlier August and October Mean Temperature Profiles by Lübken and von Zahn (JGR, 1991).